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Research article

SPATIAL DISTRIBUTION OF *SAHLBERGELLA SINGULARIS* HAGL. (HEMIPTERA: MIRIDAE) POPULATIONS AND THEIR DAMAGE IN UNSHADED YOUNG CACAO-BASED AGROFORESTRY SYSTEMS

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ABSTRACT: The population dynamics of African cacao mirids have been widely studied in shaded cacao systems, which are predominant in most of the cocoa producing countries. The current establishment of new cacao systems in Cameroon enables us to study mirids and the spatial distribution of their damage in six unshaded cacao plantations that are down on savannah and forest regions. We assessed mirids density through visual counts of individuals and damage by scoring dry leaves on branches and cankers on branches and trunks. Our results showed that the mirid populations were low and aggregated on few cacao trees. Mirid spatial distribution was structured in half of the plots and trees with mirids were grouped in distinct areas and/or scattered throughout the plots. Dry leaves damage was low but more widely spread with a spatial distribution less structured than mirid populations. Canker damage was high and their spatial distribution was structured, with some areas more infested. Since cankers accumulated on branches during the 4-years period following plot establishment, our results provide information about the history of mirid infestation in the plots. Despite the aggregation of mirid populations in the plots, infestation areas vary over space and time. However, the presence of higher infestations in some areas in the plots could indicate that there are zones that offer better ecological conditions to mirids. Our study contributed to a better knowledge of population dynamics for cacao mirids in sunny habitats as well as their damage; and these should be taken into consideration for integrated pest management strategies against *S. singularis*.
Key words: Spatial pattern, *Theobroma cacao*, cocoa mirids, damage, population dynamics

INTRODUCTION

The brown cacao mirid, *Sahlbergella singularis* Haglund, is the most harmful insect pest of cacao in Cameroon [1,2,3] and a serious pest in other major cacao producing countries in West Africa, like Ivory Cost [4,5] and Ghana [6]. Cacao mirids feed by inserting their mouth parts into the plant tissues, injecting saliva into the lesion, and sucking the digestion products. The saliva has a marked histolytic effect probably due to the activity of the esterase [7]. Damage due to mouthpart insertion and saliva action is strong enough to cause the death of young shoots. In contrast, damage is usually less important on lignified tissues of hardened twigs and stems. The presence of pathogenic opportunistic fungi such as *Albonectria rigidiuscula* (Berk. and Br.) formerly known as *Calonectria rigidiuscula* in the feeding lesions has been reported [8]. Mirid and fungi attacks result in cankering or bark roughening, destruction of the flower cushions, severe dieback of twigs and branches, and sometimes partial degradation of cacao farms. High numbers of feeding punctures may cause a distortion of young pods during growth, or even death of severely damaged fruits [3]. To the best of our knowledge, yield losses attributed to mirids alone have not been precisely assessed in Cameroon. However, it is thought that cacao mirids may be responsible for yield losses that are higher than 25% in West Africa [9]. Actually, in Cameroon, cacao mirids are generally controlled by chemical spraying. A wide range of spraying practices, sometimes very different from those recommended by agricultural extension has been reported [10,11,12]. Common problems related to chemical use by smallholders in the developing countries are true for Cameroonian cocoa farmers: (1) high costs and low availability of chemicals and spraying equipment, especially in rural zones, (2) lack of farmers' knowledge on good use of pesticides notably spraying practices, (3) environmental pollution, biodiversity disruption and impact on natural enemies, (4) risk for farmers' health as well as consumers' one through chemical residues in cocoa beans [9,13,14,15,16]. Although research has been oriented for many years towards the development of more sustainable control strategies, no practical alternative to chemical control is implemented by farmers today.

Mirid population dynamics has been studied in traditional cacao agroforestry systems, which are shaded multi-strata, highly heterogeneous and diversified systems [2,17,18]. In these systems, mirids are aggregated where cacao trees are exposed to direct sunlight through shade canopy breaks [1]. By contrast, data on mirid population dynamics as well as the distribution patterns of mirids and their damage in unshaded cacao plantations are scarce and need to be determined for a better knowledge of mirids distribution under different growing cacao systems.

Since 2006, innovative intercropping cacao systems are being developed in collaboration with the farmers in the Centre region of Cameroon. In these systems, cacao is intercropped with several plant species such as fruit trees, banana, oil palm and coconut trees. Cacao and the associated plants are grown at the same time. Since, cacao trees grow in unshaded conditions because the associated plants are not high enough to provide shade. In this study, the overall objective was to characterize the distribution of current mirid populations and damage as well as a history of mirid distribution through cumulative damage, under unshaded and relatively homogenous cacao growing conditions.

MATERIAL AND METHODS

Study sites and experimental plots

The study was conducted over two consecutive years (2009 and 2010) in six cacao plantations that are spread over two sites in the Centre region of Cameroon. The original vegetation of this region is a semideciduous rain forest, with patches of bush savannah in the North [19,20]. Two plots were selected in the forest area near the village of Ngat (3°46'N and 11°49'E), noted Nga1, Nga2. Four plots were selected in the forest-savannah area near the village of Bokito (4°34'N and 11°06'E), noted Bok1 to Bok4.The selected plots were four-years-old and approximately 0.3 hectare. Intercropping designs were of two types: 1) rows of cocoa trees intercropped with rows of oil palm or coconut trees for plots Bok1 (Fig. 2A), and 2) rows of cacao trees interspaced with fruit trees (avocado, *Persea americana*, *Citrus* sp. and safou, *Dacryodes edulis*) for all the other plots Bok2 to Nga2 (Figs. 2B and C and 3A, B and C).The distance between cacao trees as well as the distance between cocoa trees and associated trees was 3 m. The distance between coconut and palm trees on rows was 6 m. At the time of plantation, cacao was also intercropped with bananas yet after two years these were eliminated and thus bananas were not present at the time of the study. At the same time, intercropped trees were not high enough to provide cacao with shade. Cacao and associated trees that dried off were replaced (<3% of the total plants in general) on a regular basis. Plot maintenance was relatively comparable between plots, with regular weeding and chemical sprayings but the number of applied chemicals in cacao plantations varied between farmers with at least three times per year.

We collected climatic data by using a thermometer (Littoclime S.A., Caen, France) that was placed under a covering house of farmer for measure daily temperature and pluviometer (Littoclime S. A., Caen, France) placed on the compound of farmer for measure daily rainfall.

Evaluation of mirid populations

Mirid populations normally have the highest peak from July to September in Cameroon [1,21]. Thus, mirid populations were evaluated from July to September 2009 and 2010 on a weekly basis. The number of mirids per cacao tree was determined by visual counting of individuals by a local observer trained to that effect. Due to the relatively small size of cacao trees, it was possible to inspect trees wholly. Particular attention was given to the pods and especially to the areas around the peduncle and the contact zone between the pods and the bark of trunks and branches, which are known to be a shelter zone for mirids during the day [1,2,22]. Chupons which are an attractive source of food for mirids were also observed with attention. Counts were preferably done early in the morning since mirids usually escape direct sunlight by sheltering in bark crevices.

Damage observations

Feeding lesions on shoots usually induce the drying up of buds and leaves of the terminal part of branches. Dry leaves stay on trees and they are easy to detect for several weeks. After a few months, feeding lesions on shoots develop into typical cankers, accumulating on branches and roughening the bark [22].

In order to get information about infestation history, mirid damage was assessed by scoring the degree of two types of damage on branches: dry leaves, which can be qualified as recent damage, and bark cankers, which can be qualified as cumulative damage. The scoring scale was the same for the two types of damage and ranged from 0 to 3: 0 for no damage, 1 for 25% of surface of trunk and branches having damage, 2 for 50% and 3 for more than 50%. Final score given for each tree was the average scores of three experimented observers. Damage data were collected from February to mi-March 2010, i.e. during the dry season when cacao trees do not bear fruits. This period is favorable for recent damage assessment because mirid attacks are focused on shoots.

Statistical analyses

In our study, mirid distribution was characterized using two different methods, the fitting to a negative binomial distribution (NBD) and the analysis of semivariograms (SV). NBD was applied to characterize the distribution of mirid densities, whereas SV was used to characterize the spatial structure of distributions of both mirid populations and damage.

Fitting to a negative binomial distribution (NBD)

For each plot, the distribution of mirid densities was fitted to a NBD. To check the fit of the distribution of mirid densities to a NBD, observed density values were compared to expected ones, obtained from the following formulas [23,24]:

$$P(X=n)=\left(\frac{k+n-1}{n}\right)\left(\frac{\mu}{\mu+k}\right)\times P(X=n-1)$$

Where *P(X=n)* is the probability of the sampled cocoa tree having *n* individuals, μ is the mean density and *k* is a parameter of aggregation given by the formula:

$$k=\frac{\mu^2}{\sigma^2-\mu}$$

When $k\rightarrow 0$, populations are aggregated, whereas when $k\rightarrow\infty$ populations are randomly distributed or follow a Poisson distribution.

Comparisons were processed using a χ^2 test with the package software XLSTAT (version 2007.6) [25].

Analysis of semivariograms

Spatial distribution of mirid populations and their damage were characterized by fitting theoretical models to observed Semivariance using GS$^+$ software (version 9) [26]. First, Cartesian coordinates X and Y were given in meters for each cacao tree and semivariance was calculated following the formula:

$$\gamma(h)=\frac{1}{2N(h)}\sum_{N(h)}\left[z_i-z_{i+h}\right]^2$$

Where z_i and z_{i+h} were the log$_e$-transformed number of mirids plus one or the log$_e$-transformed damage scores, for each cacao tree at point i and $i+h$ respectively and $N(h)$ was the total number of pairs of cacao trees observed for the distance interval *h,* expressed in meters.

In our study the active lag distance, which is the range over which semivariance was calculated, was set at 50% of the maximum distance between any two points of the plot assessed. The lag class distance interval, which is the interval between the classes of distances *h* was set at 3 meters (the minimum distance between two cacao trees).

The quality of observed SV fitting to theoretical models was assessed by the calculation of the residual sum of squares (*RSS*), with a good fit when $RSS\rightarrow 0$ and a determination of the coefficient of determination (R^2), with a good fit when $R^2\rightarrow 1$. Therefore, the theoretical model with the smallest RSS was chosen.

Analysis of SV models gave three parameters, which are useful to characterize spatial structure of distributions: (1) the sill which is the asymptote of the model, (2) the range corresponding to the distance *h* at which the curve reaches the sill (in meters in our study), (3) the nugget variance which is the y-intercept of the model. When the SV models reach the sill, the semivariance is supposed to remain stable. Therefore the sill represents the spatially independent variance. The range gives the distance over which spatial dependence exists. The nugget variance gives the part of the variance not spatially dependent over the range.

RESULTS

Climatic data

Figure 1 reveals that the climate of our studied zones has a bimodal rainfall regime with two drier and rainy seasons. During the study, climate showed variations between sites and between the two years of observation. For instance, year 1 was dryer than year 2 for the two sites. Thus, at Bokito village, the mean annual rainfall was 105.2 ± 97.9 mm in 2009 and 109.1 ±84.9 mm in 2010 and the mean daily temperature was 29.9 ± 2.2°C in 2009 and 27.0 ± 2.3°C in 2010. At Ngat, the mean annual rainfall was 108.0 ±103.8 mm in 2009 and 137.4 ± 122.3 mm in 2010 and the mean daily temperature was 27.8 ± 0.7 °C in 2009 and 28.2 ± 1.6°C in 2010.

Mirid densities and damage scores

A total of 239 individuals of *Sahlbergella singularis* were recorded during this study and distributed as 112 individuals in 2009 and 127 in 2010. Only 3.9% of the total number of cacao trees observed for the two years sheltered mirids. The overall mean density was low with 0.19 ± 0.11 mirid tree^{-1} in 2009 and 0.31± 0.37 mirid tree^{-1} in 2010. Mean density (*M*) varied between plots and years (Table 1). One plot did not show mirids for one year of observation (Bok4). Mean densities per cacao tree ranged from 0.04 mirid for plot Bok3 in the year 2010, to 0.97 mirid for plot Nga1 in the year 2010. A maximum of 63 mirids were observed on a cacao tree of plot Nga1 in 2010. This plot also gave the maximum value for the number of trees sheltering mirids, with 42 (13%) among 322 observed trees in 2010. The variance of density (S^2) was constantly higher than the mean for plots with mirids, suggesting an aggregated distribution pattern of mirid populations in the studied cacao plantations.

Dry leave damage scores were low for all plots compared to canker damage scores, with scores ranging from 0.54 ± 0.66 for plot Nga2 to 0.85 ± 0.62 for plot Bok4 for dry leaves against 1.11 ± 0.47 for plot Bok1 to 1.96 ± 0.53 for plot Bok4 for cankers (Table 2).

Distribution of mirid densities

Fitting the negative binomial distribution

Our results show that the distribution of mirid densities fitted the NBD for nine cases among the 11 cases for both years with mirids (Table 1). The *k* value was variable, but constantly low, ranging from 0.006 to 0.068, with an average value of 0.025. These results confirm that mirid populations were aggregated in most cases under investigation.

Table-1: Main statistical parameters for mirid density for each plot and year, and for the fitting of density distribution to a negative binomial distribution (NBD), with N° C. trees.: number of observed cocoa trees, N° Oc. trees.: number of occupied trees, Max: maximum density value, with densities expressed in No. individuals tree^{-1}.

Plot	Year	N°.C trees	N°Oc. trees	Density parameters			Fitting to NBD			
				Max.	*M*	S^2	*K*	Obs. χ^2	d.f.	p-value
Bok1	2009	347	4	40	0.17	4.93	0.006	17.50	39	0.014*
	2010	373	11	12	0.16	1.14	0.025	5.23	11	0.632
Bok2	2009	325	16	20	0.26	2.26	0.032	9.85	19	0.197
	2010	373	15	15	0.18	1.28	0.029	7.46	14	0.383
Bok3	2009	355	15	23	0.26	3.28	0.022	12.59	14	0.083
	2010	358	3	10	0.04	0.31	0.006	9.62	3	0.211
Bok4	2009	175	13	10	0.30	1.59	0.068	4.05	9	0.774
	2010	202	0	0	0	0	-	-	-	-
Nga1	2009	319	3	7	0.05	0.26	0.010	13.68	6	0.057
	2010	322	42	63	0.97	27.77	0.035	15.81	62	0.027*
Nga2	2009	309	5	12	0.07	0.56	0.009	10.07	11	0.185
	2010	340	21	27	0.49	7.12	0.036	14.86	26	0.038*

*Does not follow a negative binomial distribution at the 5% level.

Table-2: Damage scores (March 2010) for dry leaves and cankers for each plot. Score for a plot is the mean for the number of observed cocoa trees (No.) of the means of three notes given by three different observers. Means (*m*) are given with standard errors (*SE*).

Plot	No.	Damage scores	
		Dry leaves (*m* ± *SE*)	Cankers (*m* ± *SE*)
Bok1	349	0.65 ± 0.50	1.11 ± 0.47
Bok2	347	0.63 ± 0.52	1.60 ± 0.79
Bok3	350	0.57 ± 0.26	1.45 ± 0.60
Bok4	179	0.85 ± 0.62	1.96 ± 0.53
Nga1	285	0.63 ± 0.65	1.48 ± 0.43
Nga2	300	0.54 ± 0.66	1.60 ± 0.41

Spatial distribution of mirid populations and damage

Distribution maps

Figure 2 and 3 show the distribution maps of mirid populations and damage for the six studied plots, Bok1 (Fig. 2A), Bok2 (Fig. 2B), Bok3 (Fig.2C), Bok4 (Fig. 3A), Nga1 (Fig. 3B), and Nga2 (Fig. 3C). The maps reveal that the mirid populations were sheltered by a few cacao trees, while the majority of cacao trees were free from mirids. Different distribution patterns are observed for infested cacao trees. The infested cacao trees were scattered throughout the plots Bok2, Bok3, Bok4, Nga2 and Nga1 in 2009 and tended to be aggregated in a corner for plots Bok2 in 2009, Bok3 in 2009 and Nga1 in 2010. The population of plot Bok1 was relatively less aggregated than that of Nga1 and Nga2 and was more aggregated than that of Bok2, Bok3 and Bok4.

On the contrary to mirid populations, mirid damage was largely scattered throughout the plots. However, their spatial distribution varied between plots and according to damage type (Figs. 2A, B and C and 3A, B and 3C). Maps for damage of dry leaves show that at least half of the cacao trees have been recently attacked. Most of the trees were attributed the score 1 (71% of the total of cacao trees), and some of them score 2 (28%) and score 3 (1%).

In plot Bok1, damaged trees tended to be grouped but this was not so clear for the five other plots, where damaged trees were more scattered throughout the plot. Maps for canker damage show that the most part of plots (≥ 80% of the total of cacao trees in general) were damaged (Figs. 2A, B and C and 3A, B and C). Damaged cocoa trees with score 2 were the most numerous in plots Bok2, with around 110 trees out of the 302 infested ones, 120 trees out of 219 for Bok3, 100 trees out of 187 for Bok4, 100 trees out of 276 for Nga1 and 140 trees out of 300 for Nga2 compared to plot Bok1 where around 50 trees scored this score out of 320. The number of trees with score 3 was far higher in plot Bok2 (75 trees) compared to plots Bok3 (38 trees), Bok4 (36 trees), Bok1 (9 trees), Nga1 (15 trees) and Nga2 (22 trees). Trees with highest damage scores tended to be grouped in the plots (Figs. 2A, B and C and 3A, B and C), with some parts of the plots being more damaged than others.

Analysis of semivariograms (SV)

Semivariograms for mirid populations fitted to two models: exponential (Figs. 4A, B-2010 and Figs. 5A-2009 and 5C-2010) and linear (Figs. 4B, C-2009 and Fig. 5B-2010). Fitting to models was globally good with RSS values ranging from 0.0008 to 0.0104 and R^2 values varied from 0.540 to 0.891. For exponential models, the range was 5.5 meters for Bok1 (Fig. 4A), 7.32 meters for Bok2-2010 (Fig. 4B), 9.15 meters for Bok4 (Fig. 5A) and 5.6 meters for Nga2 (Fig. 5C). The exponential models we obtained suggest a highly spatially structured distribution of mirid populations. Linear models were obtained for Bok2-2009 (Fig. 4B), Bok3-2009 (Fig. 4C) and Nga1-2010 (Fig. 5B). For linear models, the sill is never reached for the considered distance and the range can be considered as infinite. Therefore, the three linear models we obtained showed a constant spatial dependence for mirid density over the whole distance of analysis. Our linear models also showed relatively high values of nugget variance, which accounted for a large part of the semivariance. This result suggests that the proportion of spatially structured variance of mirid density was low, in other words, that mirid spatial distribution was not spatially structured within the three plots considered.

Semivariograms for dry leaves fitted to spherical model for plot Bok1 (Fig. 4A), to an exponential model for plot Bok2 (Fig. 4B), and to linear models for four plots, Bok3 (Fig. 4C), Bok4 (Fig. 5A), Nga1 (Fig. 5B) and Nga2 (Fig. 5C). Fitting to models was globally good with RSS values ranging from 0.0004 to 0.0019 and R^2 values varied from 0.638 to 0.960. Spherical model for Bok1 had a high range, with 53.18 meters, and a high nugget variance, so that it was similar to linear models for plots Bok3, Bok4, Nga1 and Nga2. Exponential model for Bok2 had a range of 8.19 meters and a low nugget variance. These results suggest that the distribution of dry leaves were not spatially structured for five plots out of the six studied plots.

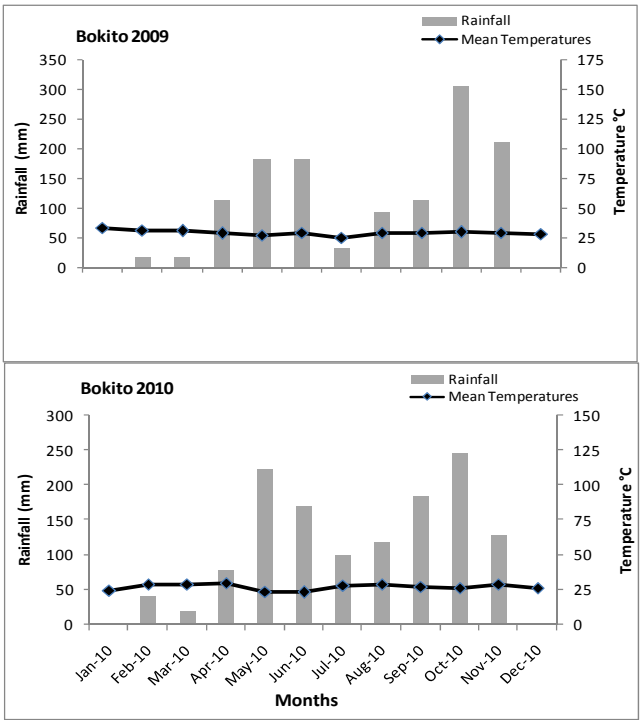

Figure-1A

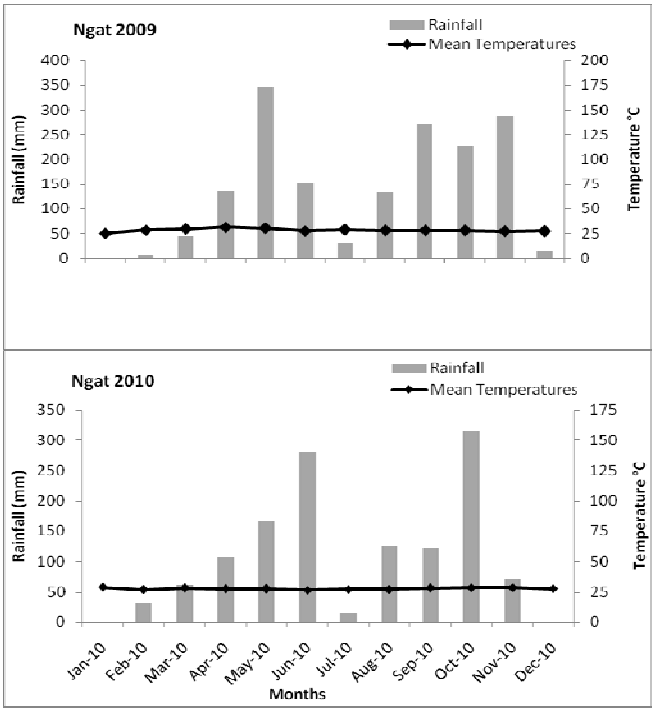

Figure-1B

Figure-1: Ombrothermic diagrams of both study sites, Bokito (A) and Ngat (B)

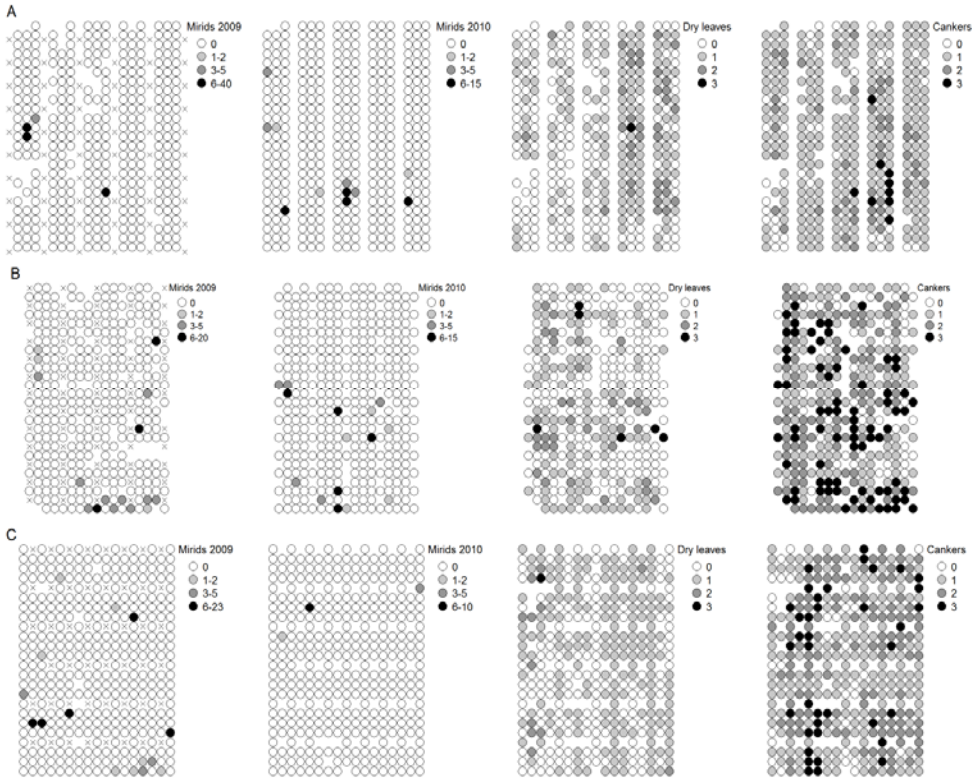

Figure-2: Distribution maps for mirid populations and damage for plots Bok1 (A), Bok2 (B), and Bok3 (C). Filled circles show position of cocoa trees and small crosses show position of intercropped trees, i.e. palm trees for plot Bok1 (A) and a mix of citrus, avocado, and safou (*Dacryodesedulis)* for plot Bok2 (B) and Bok3 (C). Intercropped trees were represented only for first maps.The absence of cocoa trees on the rows means that the concerned ones died and might be replaced the following year.

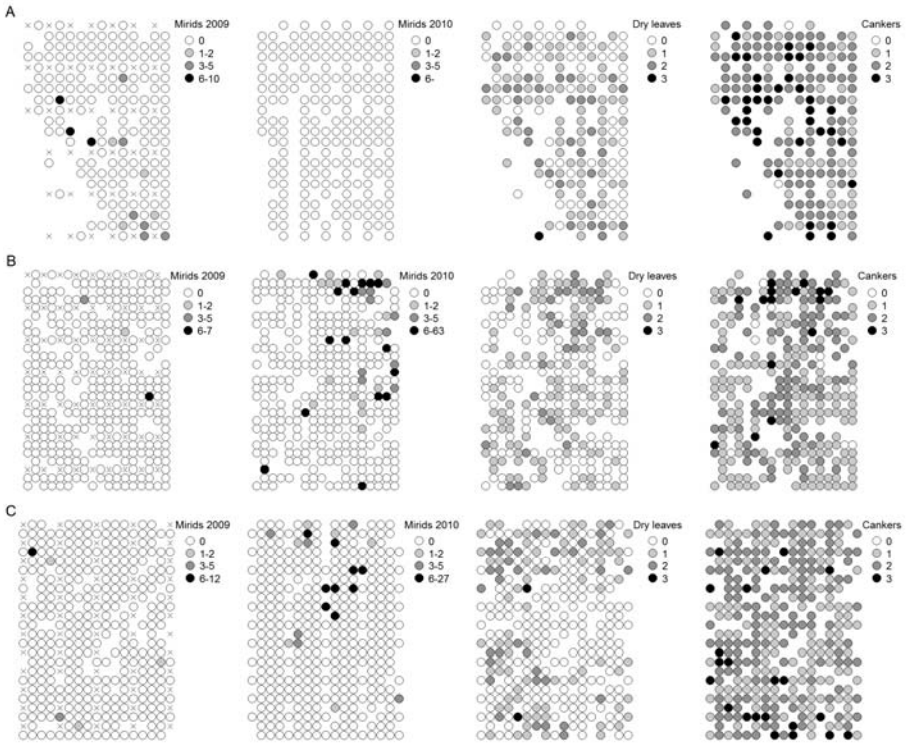

Figure-3: Distribution maps for mirid populations and damage for plots Bok4 (A), Nga1 (B), and Nga2 (C). Filled circles show position of cocoa trees and small crosses show position of intercropped trees, i.e. a mix of citrus, avocado, and safou (*Dacryodesedulis)*. Intercropped trees were not represented for damage maps and the absence of cocoa trees on the rows means that the concerned ones died.

Semivariograms for cankers fitted to exponential models for 3 plots, Bok2 (Fig. 4B), Bok4 (Fig. 5A) and Nga1 (Fig. 5B), to spherical models for two plots, Bok1 (Fig. 4A) and Bok3 (Fig. 4C) and to linear model for one plot, Nga2 (Fig. 5C). Fitting to models was globally good with RSS values ranging from 0.0006 to 0.0139 and R^2 values varied from 0.792 to 0.987. For exponential models, the range was 7.47 meters for Bok2, 12.15 meters for Bok4 and 8.46 meters for Nga1.When compared to the sill, the nugget variance was low for the exponential models. For spherical models, the range was 18.42 meters for Bok1 and 11.46 meters for Bok3. The nugget variance reached almost half of the sill for Bok1 (Fig. 4A) but was lower for Bok3 (Fig. 4C). These results suggest that the distribution of cankers were spatially structured for five plots out of the six studied plots.

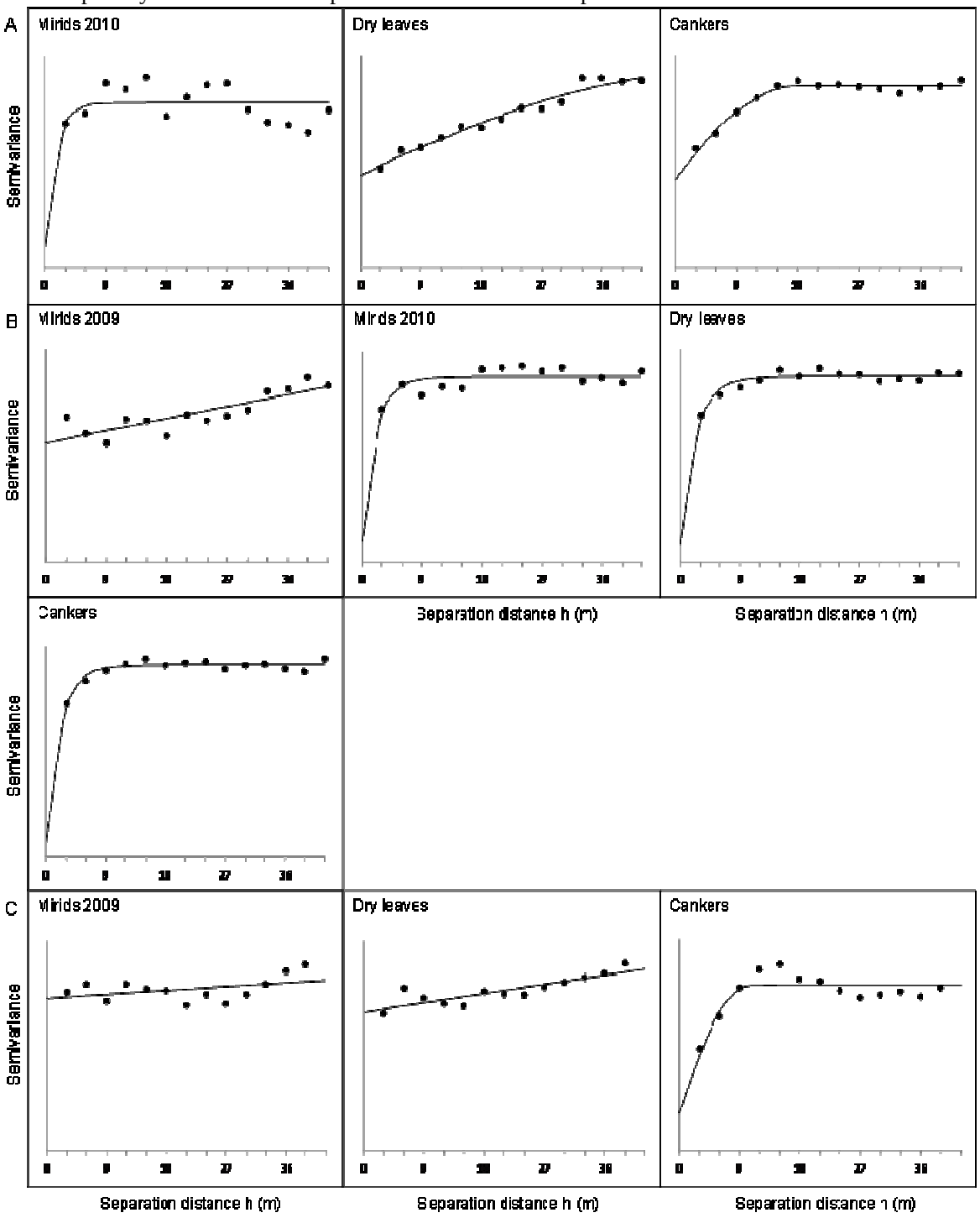

Figure-4: Semivariograms, with black dots for observed semivariance and curves for fitted models, for mirid populations and damage, for plots Bok1 (A), Bok2 (B), Bok3 (C).

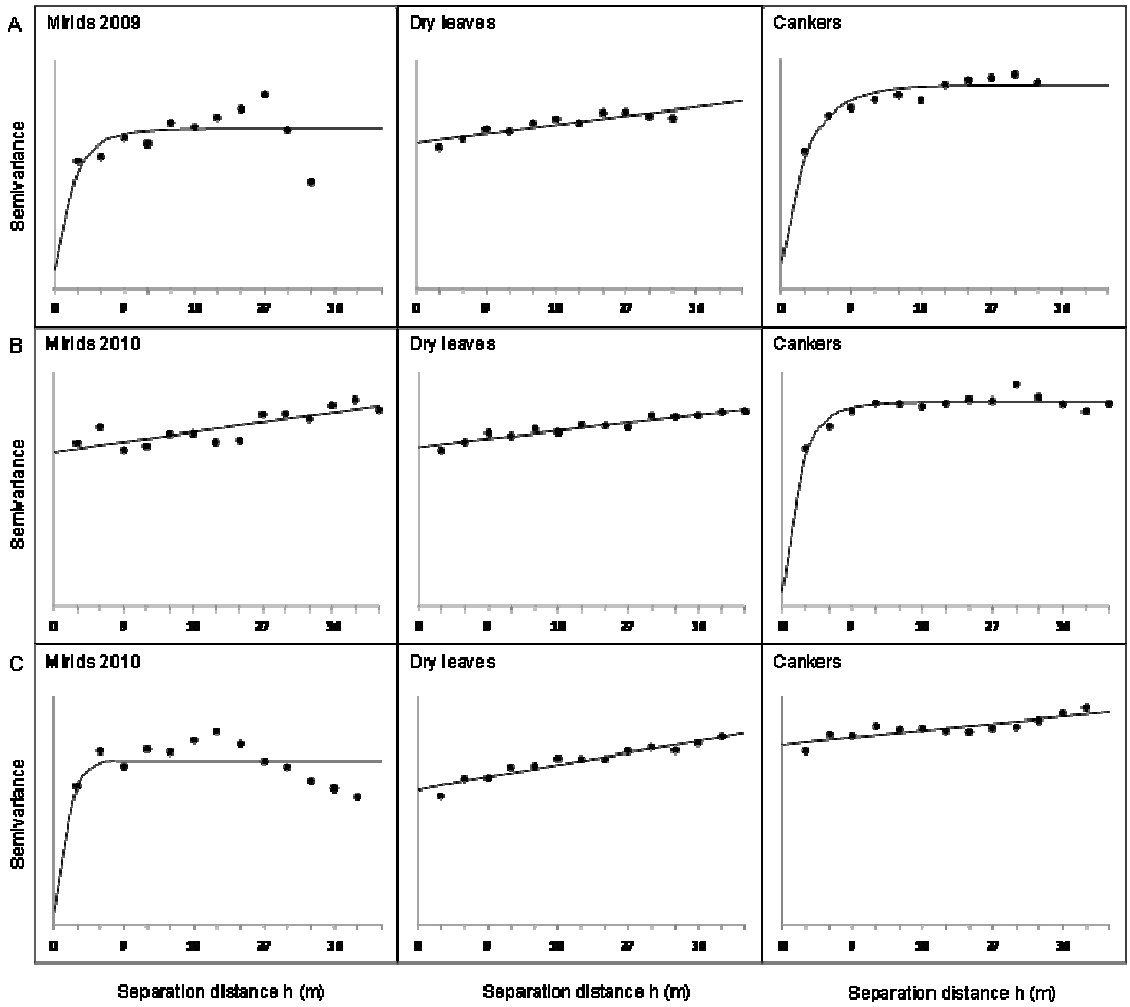

Figure-5: Semivariograms, with black dots for observed semivariance and curves for fitted models, for mirid populations and damage, for plots Bok4 (A), Nga1 (B), Nga2 (C).

DISCUSSION

With an overall mean that is lesser than 0.2 mirids per cacao tree, mirid densities were low in our study. Their populations are usually low on cacao trees, yet mirid damage is so destructive to the crop that the threshold for government spraying campaigns has been fixed at 0.7 mirid tree^{-1} in Cameroon in the late 1970s [27]. With the exception of plot Nga1, density of which exceeded this threshold in 2010, the low densities obtained in 2009 and 2010 could be explained by an intensification of the maintenance practices by farmers, especially chemical spraying, to prevent young crops from more extensive damage. Indeed, some farmers facing to high infestation level during the first two years of plots establishment increased insecticide treatments frequency in their plots (at least three times per year according to farmers' assertion) to prevent future attack. In that case, mirid populations could be low or absent from the plot as testified by our results, and this confirms the insecticide efficiency for mirid control [11]. In addition, densities measured in our study were at least 3 times lower than those measured in previous studies [1,2]. These authors found mean population densities of 0.6 and 2.1 mirids per cacao tree in shaded cacao systems, which are supposed to shelter less mirid that unshaded plantations [7,22]. Again, this seems to give evidence of the impact of chemical spraying on mirid populations. Another reason may be that the year 2009 has been particularly dry with less than 110 mm of precipitation for Bokito village from July to September 2009, compared to a mean of 400 mm for the same period of the three previous years (unpublished data). The same was true for the Ngat village, with around 150 mm from July to September 2009, compared to a mean of 490 mm for the same period of the three previous years (unpublished data). Cacao mirids are known to be sensitive to desiccation, with an optimum relative humidity rate of 90 to 95% for development [22,28]. In unshaded young cacao plantations, mirids may be more exposed to dryness with their consequences such as the dry wind and the absence of moisture for plants than in shaded ones and these could lead to high mortality in mirid populations [29,30]. Moreover, the lack of rain may have led to hydric stress for cacao trees, which is known to disturb mirid development [31].

Our results also show that when mirids were present, they were usually aggregated on cacao trees. Fitting of density distributions to the negative binomial law gave values for aggregation parameter *k* ranging from 0.006 to 0.068, which are substantially lower than those obtained by [1]. In this last work, mirid densities were far higher compared to our values and an increase in the density of an insect usually goes with a change in distribution and consequently in a different aggregation parameter *k* for the population [24].

Our findings concerning the distribution maps and semivariograms also revealed that, even if the mirids were grouped on some trees, their spatial distribution varied between plots and years. The linear semivariogram obtained in plots Bok2-2009, Bok3-2009 and Nga1-2010 (see Figs. 3 and 4) revealed that, in these plots, spatial distribution of populations was not structured, in other words, that infested cacao trees were not grouped but scattered throughout the plot. In contrast, in the other plots (Bok1-2010, Bok2-2010, Bok4-2009 and Nga2-2010), distributions were more structured with spatial dependence ranging from 5.5 to 9.15 m, suggesting that mirids were present on groups of nine to 29 cacao trees. This result is more consistent with what has been qualified as "mirid pockets" by previous works [1,22]. A "mirid pocket" has been defined as a small group of cacao trees which sheltered a high density of mirids in the plantations and showed a highly damaged contrast with the surrounding healthy cacao [7]. In a recent work, "mirid pockets" has been shown to be located in the sunniest areas of shaded cacao farms [1]. In our study, shade can't be involved in the location of "mirid pockets" and spatial distribution of mirid populations must result from other factors. As mirids has been shown to be differently attracted by shoots from different cacao varieties, a possible factor explaining mirid distribution could be cacao variety associations that are different from a plot to another [5,32]. To confirm these hypotheses, further studies taking into account the different incriminated factors should be carried out.

Our results also show that, contrary to mirid populations, mirid damage was high, especially cankers which, as cumulative damage, give information about the history of mirid infestation in the studied plots. High scores obtained for canker notation suggest significant mirid attack in at least one of the four years since the plots were established in 2006, or lower but more constant infestation over an extended period during the four years, or a combination of both. This result could be linked to mirid feeding and reproductive behaviour in nature. Indeed, it is possible that mirids, especially adult stage which colonize new plantations ,used cacao trees as a food source only but not for reproduction so that populations did not settle for the long term. Then, damage in our plots could be due to mirid adults coming from the surrounding environment of plots, and not from populations present in the plot itself. There was no obvious positive relationship between density of mirid populations and their damage. Some plots such as Bok1 and Nga1, showed high values of mirids density (Table 1) but did not show high damaged cacao trees (Table 2).

We assessed mirid damage by scoring dry leaves and cankers on trees in February-March 2010. Dry leaves are recent damage that should have been linked, in our study, to mirid populations for 2009. But distribution maps showed that damage of dry leaves was far more widely spread than mirid populations assessed in July-September 2009. Semivariogram analysis also showed that for dry leaves spatial distribution was mostly not structured. These results suggest that in the six months before damage assessment, which correspond to three to four mirid generations [28], adult populations could have widely moved throughout the plots for food but could have led eggs on some cacao trees which offered good ecological conditions in term of habitat/food for their offspring. This situation can explain a high density of mirid population and high score for cankers on some trees and the homogeneous spatial distribution of new damage in the studied plots. Results for canker damage confirm these assumptions, since most of cocoa trees showed cankers in the studied plots. Cankers are cumulative damage and give an idea of what was infestation in the previous years, i.e. in our study from the plantation establishment in 2006 to 2009. The distribution maps for plots Bok1, Bok2, Bok3, Bok4, Nga1 and Nga2 showed that, during this period of four years, very few cocoa trees did not host mirids in these plots.

Overall, our results also suggest that mirid damage may have been overestimated by the scoring method, especially dry leaves. Indeed, damage assessment has been done during the dry period, when young cocoa trees usually suffer from drought, especially when they are grown in full sun. Then mirid damage may have been confused with hydric stress damage, which can be similar.

CONCLUSION

At the end of this study, if mirid populations were low and aggregated, damage was high and widely distributed in plots. Our results confirm the conclusion of several studies which assess that unshaded cocoa is highly exposed to mirid attacks [22,33]. In shaded plantations, populations and damage are located in the sunniest areas of the plots. On the contrary, in full-sun plantations, mirid populations and their assumed movements through time and space lead to more uniform distribution of damage. This study also raises some questions regarding the factors and mechanisms involved in the establishment of mirid populations in unshaded cocoa plots. Providing answers to these questions may be of great interest for the improvement of control strategies for cocoa mirids. In any case, by this study, we contribute to a better understanding of population dynamics of cocoa mirid in sunny habitats.

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